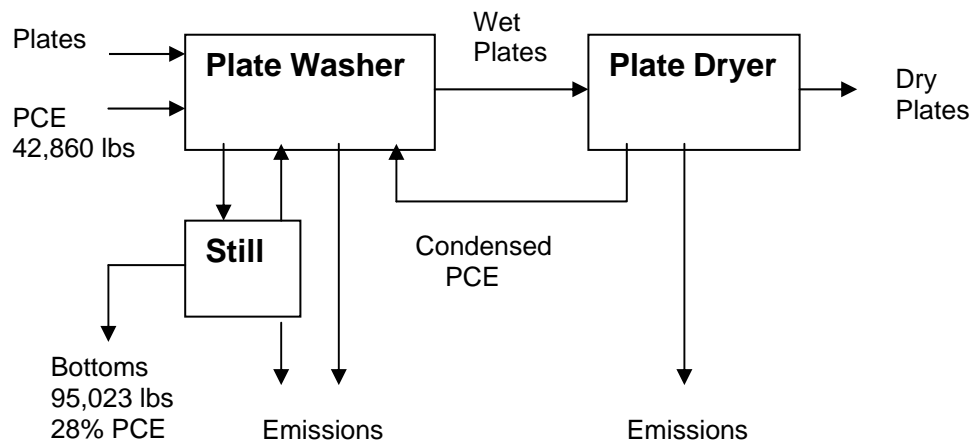




Seminar Notes For

Process Mapping And Mass Balances



Washington State Department of Ecology
Hazardous Waste and Toxics Reduction Program
Publication Number 00-04-007
Revised March 2004



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INTRODUCTION

This document contains class notes for a seminar on *Process Mapping and Mass Balances*, presented to HWTR Toxics Reduction staff in April of 2000.

This workshop provided two hours of training on diagramming and mapping industrial processes, and performing mass balances using these maps to provide guidance on how these tools can be used for pollution prevention assistance.

The training addressed topics submitted by staff and was presented in conjunction with training on *Total Cost Assessment* (TCA), because process mapping and mass balances can provide the foundation for TCA economic analysis.

Staff involved in the development of this training included Dennis Murray, John Blunt, Judy Kennedy, Scott Lamb, and Bob Goldberg.

PROCESS MAPPING

A process map identifies all the critical elements of a process and offers a structured visual layout of their sequence and relationship to one another. The work steps in the map show how the materials flow through the process. A process map is a convenient method to keep track of materials use and loss, and can be an integral part of a formal material tracking system that monitors where, and in what quantities, a material is being used within a facility.

By tracking the flow of materials, process maps can be used to find pollution prevention opportunities. For example, the environmental manager of a large metal working company used process maps to analyze the facility's use of water-soluble machine tool coolants. He discovered that 24 separate varieties of coolant were used, with the different coolants sometimes used in identical applications. A comparison of each coolant's chemical makeup revealed an opportunity to reduce the coolant selection from 24 to fewer than 10. The analyst spent half a day reviewing materials use and one week implementing the changes, resulting in cost savings of \$20,000 to \$40,000 annually on inventory, maintenance, labor, and training.

APPLICATIONS OF PROCESS MAPPING AND MASS BALANCES

Toxics Reduction staff may encounter process maps and mass balances as part of technical assistance work they do in the following areas:

Pollution prevention planning

Worksheet G in our planning guidance manual asks for process flow diagrams, narrative process descriptions, or both.

General technical assistance

Technical assistance projects such as the Toxics Reduction Engineers Exchange (TREE) and sector projects may utilize process diagrams and mass balances to analyze materials flows and estimate potential reductions that would result from pollution prevention opportunities.

TRI reporting

Mass balances are one of the methods recommended for use in accounting for toxic releases for Form R reporting.

Total Cost Assessment

Process mapping and mass balances can be an important first step in performing total cost assessments.

Systematic P2 Analysis

P2 consultant Bob Pojasek advocates the use of a systems approach for identifying P2 opportunities. This approach starts with process mapping and mass balances.

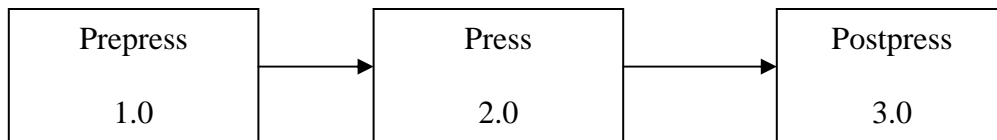
Regulatory mapping

A process map can be used to identify regulatory compliance requirements.

Creating a Process Map

A process map begins with boxes and arrows, as shown in Figure 1, depicting the sequence of steps through which inputs must pass in the course of transformation into a product.

**Figure 1. A Simple Process Map Showing
Numbered Steps in an Offset Lithographic Printing Operation**



Hierarchical Mapping

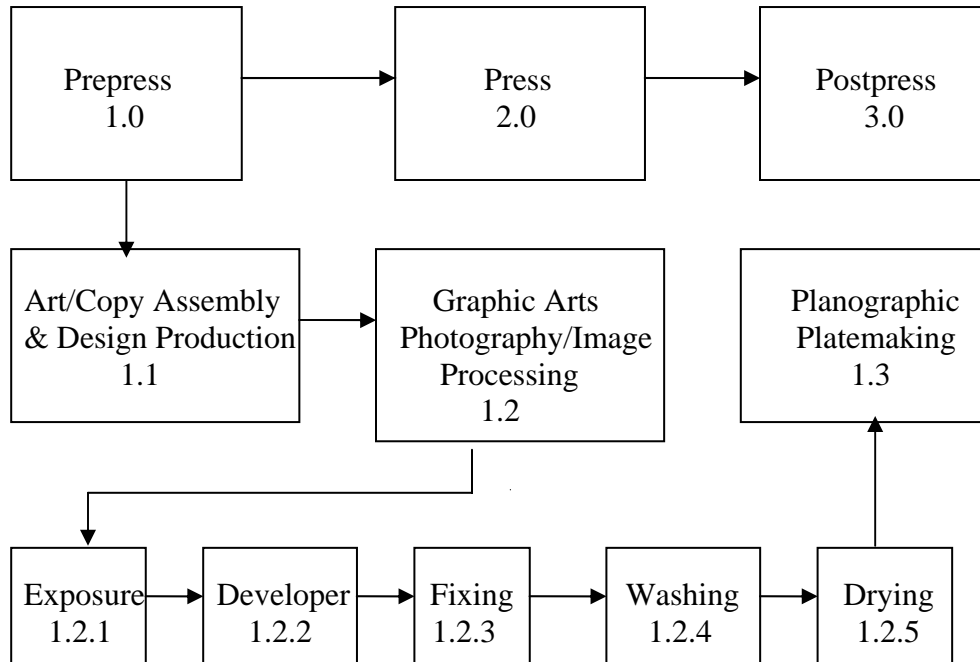
A process map actually includes a set of several maps drawn to various levels of detail. Breaking down the overall process into smaller more detailed maps provides additional specific information about the process and the source of wastes. With this specific information on the source of wastes, additional pollution prevention opportunities may be identified.

The initial top-level map (shown in Figure 1.) is intended to provide a broad overview with few details. For this reason, the top-level map should include not more than three to six work steps. This forces the creation of more detailed second- or third-level maps to describe complex process steps. The steps in the top-level map should be numbered, and it is important to maintain a consistent numbering system as a more detailed map is created.

A second level of detail can be added to a process map, to show steps involved in each top-level process. When creating the second-level maps the steps are numbered 1.1, 1.2, 1.3, etc. The first digit in each number indicates that the map is elaborating on step 1 of the top-level map. The second-level map, like the top-level map, should contain no more than six steps. If more detail is needed, third- or fourth-level maps can be created.

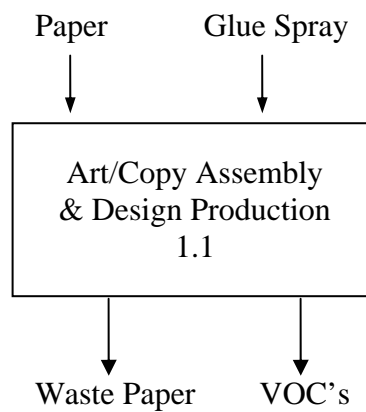
A third-level map is shown in Figure 2. Note that these third level processes are numbered 1.2.1, 1.2.2, and so forth. The first two digits of each number indicate that the map refers to step one of the top-level map and step two of the second-level map.

Figure 2. Third-Level Process Map of the Offset Lithographic Printing Operation



Process maps also depict how materials are used and wasted, as shown in Figure 3. The arrows pointing down to a box indicate the materials going into a step (inputs). The arrows leading down from the box indicate the waste (loss) and pollution created by the step.

Figure 3. A Second-level Map of the Prepress Process

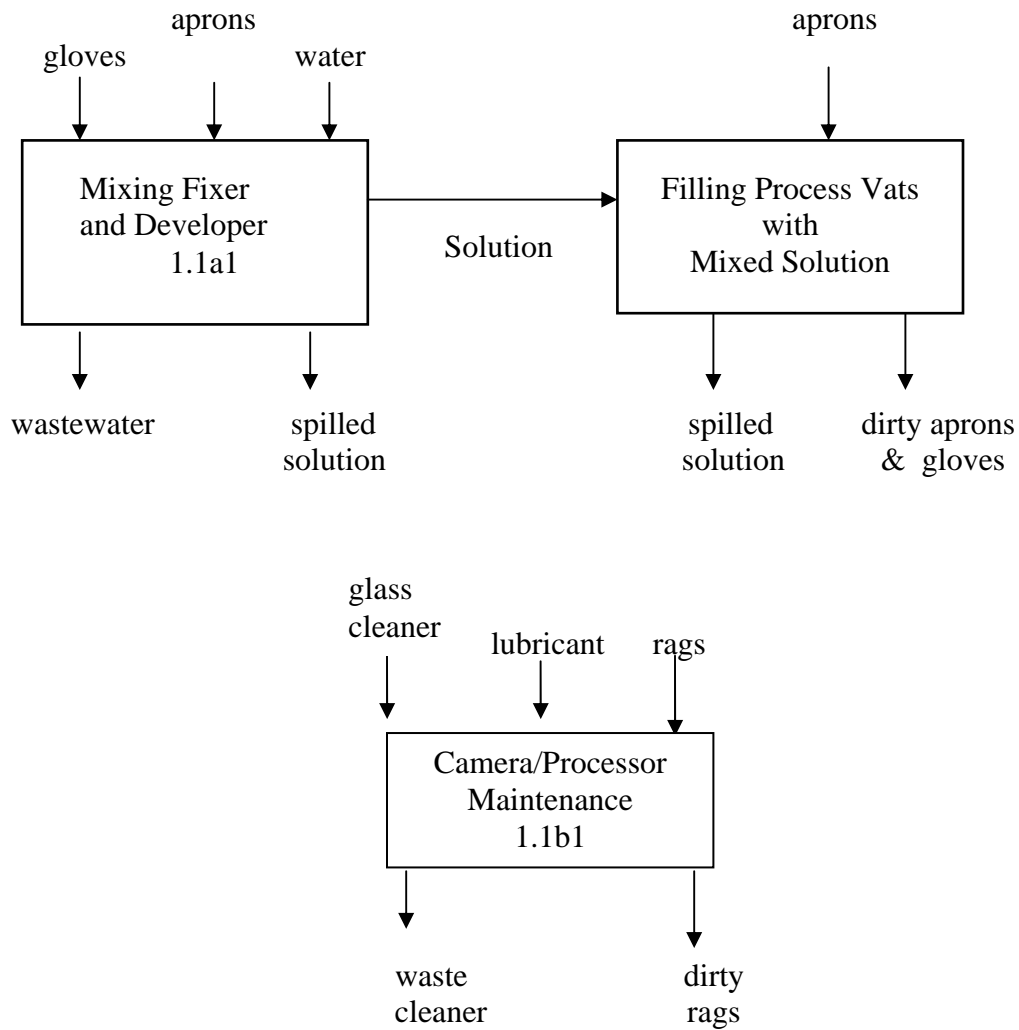


Ancillary and Intermittent Processes

So far we have addressed the main processes at a facility. Materials use and loss can occur in two other kinds of processes as well: *ancillary processes*, work steps that support the main process; and *intermittent processes*, steps such as cleaning and maintenance that are necessary for the operation of the main process. These processes often create more waste than the main process.

In a process map, the materials used or wasted in ancillary or intermittent process steps can be linked back to the work steps in the main process by using letters with the hierarchical numbers, as illustrated in Figure 4. This will enable a facility to account for all materials used and lost in all of their processes, and will assist identifying pollution prevention opportunities.

Figure 4. Intermittent/Ancillary Processes for Printing Process Step 1.1 (from Figure 3.)

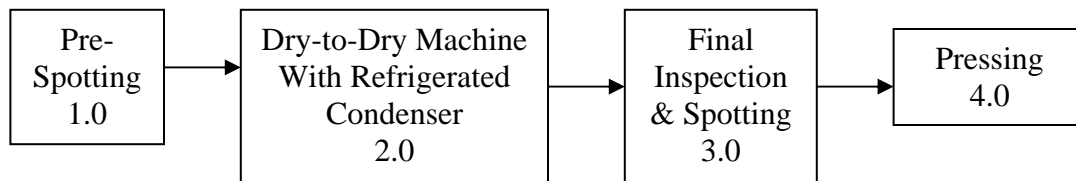


Process Descriptions

Process “maps” can be a word map as well as a diagram. Although narrative process descriptions do not offer the advantage of a structured visual layout, basing the description on a hierarchical numbering system helps to clarify the relationships of the process steps.

Figure 5. shows the sequence of primary process steps for a dry cleaning operation:

Figure 5. Main Dry Cleaning Processes



A narrative process description used to support this diagram might look something like this:

1.0 Pre-spotting

Incoming clothes are examined for stains, which are treated with steam and spotting chemicals. In the spotting operation, several water and non-water soluble chemicals are required for stain removal.

2.0 Dry-to-dry machine with refrigerated condenser

The clothes are washed with a mixture of solvent and detergent. Energy is required to drive this process, and a mixture of solvent, water, and detergent is generated as a waste. Some solvent vapors are lost to the atmosphere as employees open the machine door, and as lint builds up around the machine door seal. Other wastes include lost buttons and lint.

3.0 Final Inspection and spotting operation

Upon inspection after removal from the dryer, clothes that aren't sufficiently cleaned are spotted and cleaned again. The process is the same as that in step 1.0

4.0 Pressing

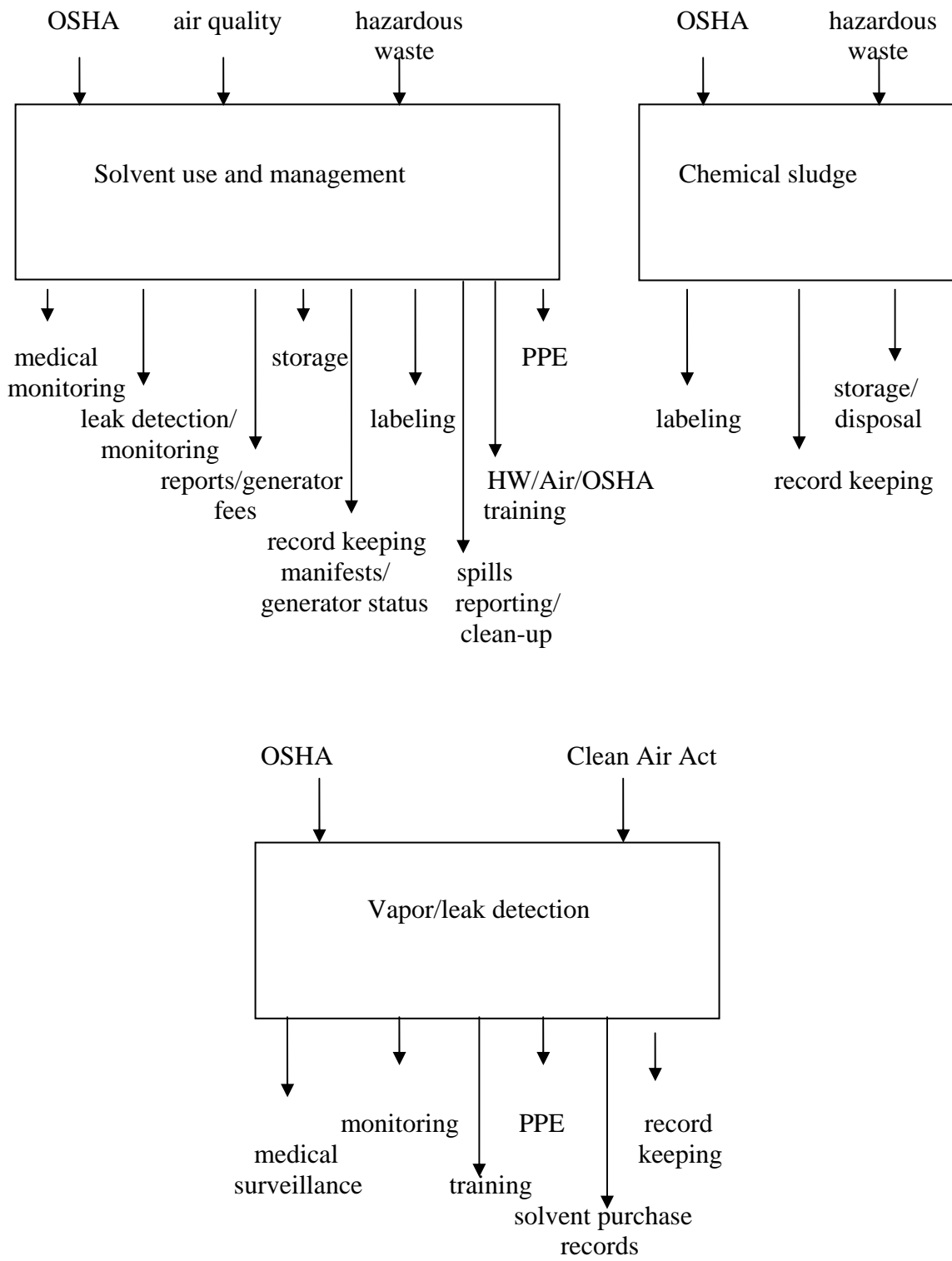
Clothes are placed on hangers and sent to the pressers. Solvent vapors may be released to the atmosphere from off-gassing from the clothes. Losses from this step may also include broken hangers or dropped clothes.

When space allows, use both a process diagram map and a supporting narrative.

Regulatory Mapping

In addition to showing materials and energy involved in process steps, process maps can be used to analyze regulatory requirements affecting processes. The regulatory map in Figure 6 shows regulatory considerations involved in process step 2.0 of the dry cleaning operation shown in Figure 5. Regulatory authorities are represented as input arrows, and the required actions are shown as outputs.

Figure 6. Regulatory Map of Dry Cleaning Process Step 2.0



Tips For Creating Good Process Maps

1. A tour of the work area where the process takes place should be conducted to verify (“ground-truth”) the process map, checking the sequence of the work steps and the materials used and lost.
2. Process maps should identify ALL the materials in and out of a process. To enhance identification of pollution prevention opportunities, include inputs and outputs such as water, force/compressed air flows, greenhouse gases, and energy.
3. It is important to date the process map.
4. The maps should be kept up to date as processes are altered. Out-of-date maps can be retained to provide a historical sequence of process modifications.

MASS BALANCES

The process diagram forms the basis for a mass balance. Each process boundary defined in a process diagram forms a boundary for analyzing mass flows. Mass balances can be formed for the aggregate of a group of processes, or for each individual process.

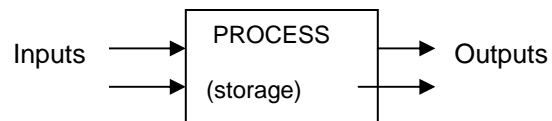
Writing and Using the Mass Balance Equation

The mass balance equation is used to account for all the material streams that contain a specific substance. A single process that involves several substances can be described with several mass balance equations, one for each substance.

The Basic Mass Balance Equation

Material enters the mass balance boundary as *inputs*, which can include raw materials, water, drag-in, recycled wastes, and environmental influx (moisture, gases, contaminants). Material exits as *outputs* such as products, byproducts and wastes, emissions, leaks and other losses. Within the boundary, material may be accumulated or depleted from *storage*. Storage can include inventory and residues in equipment. In *conservative* processes, where material is not created or reacted, the difference between the amount of material that enters and exits the boundary will be seen as a change in the amount of stored material.

$$\text{Inputs} = \text{outputs} + \text{net storage}$$

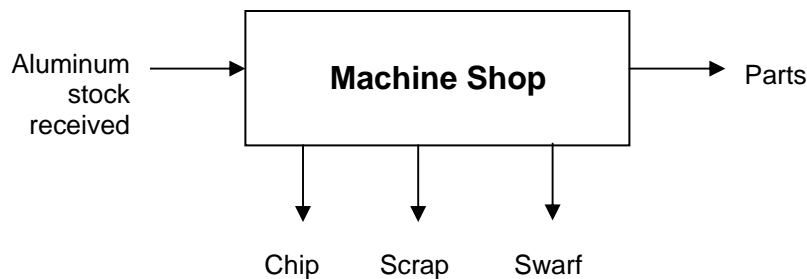


Example: Quantifying aluminum swarf disposal

A machine shop produces aluminum aircraft parts. One product line produces a part that weighs 1 pound. Production of this part generates ground aluminum (swarf). The shop has had to dispose of the swarf as solid waste. Now that it has found an off-site recycler for the swarf, it wants to estimate the pounds of swarf generated each month.

In reviewing its records, the company examined a month in which it manufactured 600 of these parts. It started with 1000 pounds of aluminum stock for this part in its inventory, received a shipment of 1000 pounds, and ended the month with 1100 pounds in its inventory. It sold 200 pounds of scrap and chip from this material to a recycler. How much swarf had been produced that month?

Drawing the boundary of the mass balance around the entire shop, the process diagram for this situation might look like this:



Inputs = 1000 lbs shipment of aluminum stock

Product output = 600 lbs

Chip and scrap output = 200 lbs

Net storage (inventory) = 1100 - 1000 lbs

Inputs = outputs + net storage

Shipment received = (product + chip + scrap + swarf) + net storage

(1000 lbs) = (600 lbs + 200 lbs + swarf) + (1100 - 1000) lbs

swarf = 100 lbs

Mixtures and Percent Composition

The mass balance equation can be modified to account for mixed or impure materials. In these cases, material can be expressed in terms of its percent mass composition. Here is an example from a TRI reporting manual:

Example: Form R reporting of nickel alloy

A steel manufacturer uses nickel (pure) to produce a steel containing 20% nickel by weight. The by-products of this process are a scrap containing 10% nickel which can be sold for recycling, and solid waste of variable nickel content that is disposed off-site. How much nickel was disposed as solid waste if in a year the facility...

- produced 24,000 pounds of product with 20% nickel
- purchased 8000 pounds of pure nickel
- produced 10,000 pounds of 10% nickel scrap
- started with nickel inventory of 4000 pounds
- ended with nickel inventory of 2000 pounds

$$\begin{aligned}\text{Inputs} &= \text{outputs} + \text{net storage} \\ \text{Purchased nickel} &= (\text{product} + \text{scrap} + \text{solid waste}) + \text{net inventory} \\ 8000 &= (.20)24,000 + (.10)10,000 + \text{solid waste} + (2000 - 4000) \\ 8000 &= 4800 + 1000 + \text{solid waste} - 2000 \\ 8000 &= 3800 + \text{solid waste} \\ \text{solid waste} &= 4200 \text{ pounds of nickel}\end{aligned}$$

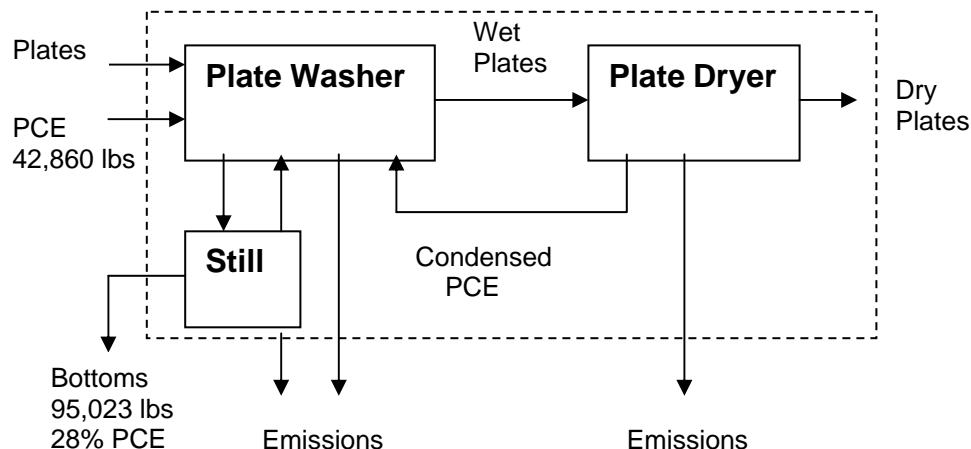
Recycled Materials

Materials that are recycled within or between processes can act as inputs and/or outputs in the mass balance equation depending on how the boundary of the mass balance is drawn. In the example of Tacoma Rubber Stamp (below), perchloroethylene (PCE) is recycled between the plate washer and still, and between the washer and dryer (Figure 7). In this example, the boundary of the mass balance is drawn around all three processes so that the internally recycled waste streams are seen in the mass balance.

Example: Tacoma Rubber Stamp

Tacoma Rubber Stamp produces flexible (polymeric) printing plates. When they filed their first Form R for TRI reporting a few years ago, they used a simple mass balance to analyze their use of perchloroethylene (PCE). They subsequently “discovered” a 16,254 lb. PCE air emission stream that had been previously overlooked.

Figure 7. Rubber Plate Cleaning Operation



(Still bottoms from this operation average 28% PCE.)

The mass balance for PCE moving through the overall system is as follows:

$$\begin{aligned}
 \text{PCE Input} &= \text{Bottoms} + \text{Emissions} \\
 42,860 \text{ lbs} &= [95.023 \text{ lbs} \times 0.28] + \text{Emissions} \\
 \text{Emissions} &= 16,254 \text{ lbs}
 \end{aligned}$$

This discovery led the facility to install a chiller to capture more of the emissions. When the efficiency of the chiller was checked with another mass balance, it was found to be very low, indicating that the chiller had not been properly installed.

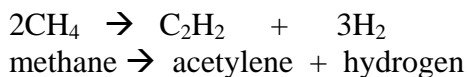
Non-Conservative Materials

Substances may be generated or consumed through reactions. For instance, a pesticide might break down or a fuel may be combusted. In such cases the materials involved are *non-conservative*. Terms can be added to the basic mass balance equation to account for material generated or consumed through reaction:

$$\text{Input} + \text{generation} = \text{output} + \text{storage} + \text{reacted}$$

Example: cracking methane to generate acetylene

The chemical formula for this reaction is:



Such chemical reaction equations are, in themselves, mass balances. If the molecular weights of the substances are added, weights on both sides of the equation balance.



$$32 \rightarrow 26 + 6$$

How many pounds each of hydrogen gas and acetylene are generated by cracking 40 pounds of methane to form acetylene? Assume the reaction is only 50% complete, and nothing is stored in the reaction chamber. Terms of a mass balance equation for *methane* would include:

$$\begin{array}{rcccccc} \text{Input} & + & \text{generation} & = & \text{output} & + & \text{storage} & + & \text{reacted} \\ 40 \text{ lbs} & + & 0 & = & 20 \text{ lbs} & + & 0 & + & 20 \text{ pounds} \end{array}$$

If we use the molecular weight ratios of the chemical reaction equation for the cracking process, we see that:

$$\begin{array}{l} \text{The ratio of acetylene to methane is } 26/32 \\ \text{acetylene} = 20 \text{ lbs methane } (26/32) = 16.25 \text{ lbs} \\ \text{The ratio of hydrogen to methane is } 6/32 \\ \text{hydrogen gas} = 20 \text{ lbs methane } (6/32) = 3.75 \text{ lbs} \end{array}$$

Determining Magnitude of Error in a Mass Balance

There are many reasons why a mass balance may *not* balance: measurement errors, calculation errors, record keeping problems, etc. In the case of Tacoma Rubber Stamp, we see that an entire material stream had initially been overlooked. The mass balance equation can be rearranged to express the magnitude of the error:

$$\frac{(\text{Outputs} + \text{storage}) - \text{Inputs}}{\text{Inputs}} = \text{error}$$

Errors can be caused by inaccuracies resulting from measurement, calculation, record-keeping, or other sources. A large error is a good indicator that the mass balance has not been properly written.

Class Exercise

Paint Line (Available in the Appendix)

This exercise involves a familiar series of process steps: a paint booth and a drying oven. There are two basic types of substances, solvent and paint solids, which occur separately or mixed together. Instruction sheet **Form A** contains the information and questions that will lead you through the exercise. Use this together with the separate sheet **Table A** showing the process diagram and spaces for recording waste stream information. Answer sheets for this exercise are included for this exercise (**Table B**).

When you are done, notice how the lower half of Tables A and B organizes mass flow information by process step and by substance. Mass balances can be written for each process step, and then checked with a mass balance for the combined steps.

How To Get the Numbers You Need

The mass quantities needed for a mass balance can come from a variety of sources, such as:

- estimates,
- regulatory reporting and monitoring forms
- sampling
- purchasing and inventory records
- manifests and bills
- air inventories and emissions factors
- direct measurements
- MSDS
- materials tracking or bar-coding systems

Case Study: Bar-coding at Fairchild Air Force Base, Spokane

Facilities can use bar-coding systems to track materials to generate valuable data for developing mass balances.

Fairchild Air Force Base has implemented an Environmental Management Information System (EMIS) that uses bar-coding to inventory and track the use of hazardous materials at the base. It reduces and prevents pollution by controlling the acquisition, use, handling, and disposition of hazardous products and wastes. The database provides information on demand levels, supply points, and customer account billings.

Bar-coding has allowed Fairchild to determine just how much material is required by a particular process. Initially, hazardous materials were issued to workers in weighed and coded canisters. The remaining content of these canisters was weighed and tracked as they were returned to the shop's inventory center. This information was used to perform mass balance calculations to determine the amount of material needed to complete a particular process step. Now workers are issued materials in pre-calculated amounts. The materials tracking system continues to use mass balances to check that materials are being used appropriately.

SOFTWARE TOOLS FOR PROCESS MAPPING

A variety of software tools are available for process mapping. Selecting the one that is right for you depends upon factors such as availability and price, complexity and ease of use, and special features that may be needed.

Ecology staff have access to drawing tools in Microsoft Office programs such as PowerPoint, Word, and Excel, that can be used for creating process maps. In each of these programs you can select “Tools” in the menu bar, and then select “Customize”. Under the tab titled “Toolbars”, select “Drawing”. This will produce a toolbar at the bottom of your screen that can be used to draw boxes, arrows, lines, and labels for process diagrams.

Other diagramming software is commercially available, with features such as:

Palettes	Linking	Templates	Auto Connecting
Drawing Tools	Symbols Library	Show Features	Types of Files

NWRO staff have also been using *Visio* software, a full featured diagramming program providing templates for flow charts, organizational charts, mapping, TQM, project timelines, computer networks, office layouts, forms and more.

Information on software products for diagramming is available at:

<u>Name</u>	<u>Company</u>	<u>WWW Link</u>
Edge Diagrammer	Pacestar	www.pacestar.com
Flow Charting PDQ	Patton & Patton	www.patton-patton.com
Powerpoint	Microsoft	www.microsoft.com
SmartDraw	Smartdraw	www.smartdraw.com
Visio	Visio	www.visio.com

RELATIONSHIP TO TOTAL COST ASSESSMENT

Because process maps and mass balances track all material inputs and losses in a process, they can form the basis for Total Cost Assessment (TCA). Total Cost Assessment is the long-term, comprehensive financial analysis of the broad range of a facility’s costs and savings. Process mapping and mass balances provide a facility an improved basis for understanding the expenditures they incur with a process, thus allowing them to more accurately assign costs to various activities.

Process mapping and mass balances are necessary to track overhead costs to products and services by identifying the resources, activities, costs, and quantities needed to produce output. A facility using process mapping and mass balances is able to identify and include the *types* of costs and benefits (i.e., “cost inventory”) that will help to demonstrate the financial viability of investments in pollution prevention.

Appendix:
Paint Spray Line Exercise

Paint Spray Line Mass Balance Exercise

A paint spray line is applying high-solids paint to parts that move from a spray booth to a drying oven. The paint contains a VOC solvent (25% of the weight of the paint formula). The rest of the formula consists of material that will become solid. Out of every 10 lbs of paint sent to the booth, 8 lbs is sprayed with a 50% efficient gun, and 2 lbs are wasted when flushing the gun and supply lines. The lines are flushed with 4 lbs of the same VOC solvent contained in the paint.

A. Instructions

Fill in the material quantities requested on the exercise diagram sheet. This sheet is already marked with the material quantities given above. Then answer the following questions:

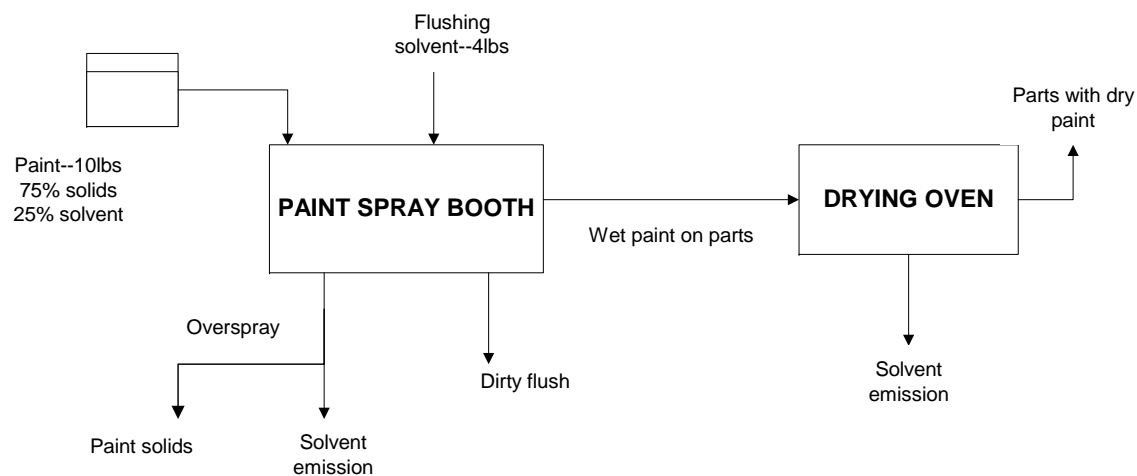
1. What percent of the paint supply ends up on parts?

2. What are the total emissions from the paint line?

3. What is the percent of solids in the flushing waste?

4. Check your work by doing an overall mass balance for paint solids for the combined paint line. Do the same for solvent streams.

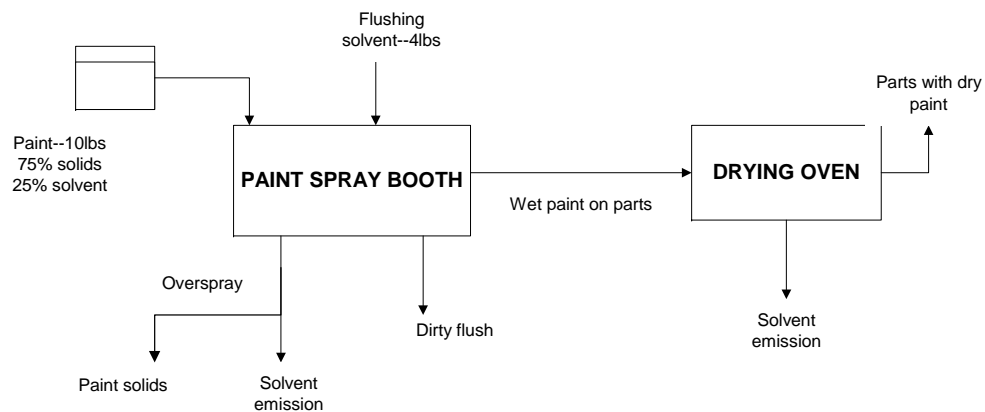
Paint Line Exercise



Material	Paint Booth (lbs)	Parts Transfer (lbs)	Drying Oven (lbs)
Whole paint streams			
Paint supply	10		
Overspray	4		
Flushed paint supply	2		
Wet paint on parts			
Paint solids streams			
Paint supply solids			
Overspray solids			
Dirty flush solids			
Paint solids on wet parts			
Paint solids on dry parts			
Solvent streams			
Paint supply solvent			
Flush solvent	4		
Overspray solvent emission			
Dirty flush solvent			
Paint solvent on wet parts			
Emissions from dryer			

Paint Line Exercise

Answers



Material	Paint Booth (lbs)	Parts Transfer (lbs)	Drying Oven (lbs)
Whole paint streams			
Paint supply	10		
Overspray	4		
Flushed paint supply	2		
Wet paint on parts	4	4	4
Paint solids streams			
Paint supply solids	$10 (.75) = 7.5$		
Overspray solids	$4 (.75) = 3$		
Dirty flush solids	$2 (.75) = 1.5$		
Paint solids on wet parts	$4 (.75) = 3$	$4 (.75) = 3$	
Paint solids on dry parts			$4 (.75) = 3$
Solvent streams			
Paint supply solvent	$10 (.25) = 2.5$		
Flush solvent	4		
Overspray solvent emission	$4 (.25) = 1$		
Dirty flush solvent	$4 + [2 (.25)] = 4.5$		
Paint solvent on wet parts	$4 (.25) = 1$	$4 (.25) = 1$	
Emissions from dryer			$4 (.25) = 1$

Paint Spray Line
Mass Balance Exercise
Answer Sheet

A paint spray line is applying high-solids paint to parts that move from a spray booth to a drying oven. The paint contains a VOC solvent (25% of the weight of the paint formula). The rest of the formula consists of material that will become solid. Out of every 10 lbs of paint sent to the booth, 8 lbs is sprayed with a 50% efficient gun, and 2 lbs are wasted when flushing the gun and supply lines. The lines are flushed with 4 lbs of the same VOC solvent contained in the paint.

B. Instructions

Fill in the material quantities requested on the exercise diagram sheet. This sheet is already marked with the material quantities given above. Then answer the following questions:

3. What percent of the paint supply ends up on parts?

$$\frac{\text{Wet paint on parts}}{\text{Paint supply}} \times 100 = \frac{4}{10} \times 100 = 40\%$$

4. What are the total emissions from the paint line?
 2 lbs.

3. What is the percent of solids in the flushing waste?

$$\begin{aligned} \frac{\text{Dirty flush solids}}{\text{Dirty flush solvent}} &= \frac{\text{Dirty flush solids}}{\text{Flushing solvent} + \text{solvent in flushed paint}} \\ &= \frac{1.5}{4 + [2(.25)]} \times 100 = 25\% \end{aligned}$$

5. Check your work by doing an overall mass balance for paint solids for the combined paint line. Do the same for solvent streams.

$$\begin{aligned} \text{Solids: } \text{supply solids} &= \text{overspray solids} + \text{flush solids} + \text{solids on parts} \\ 7.5 &= 3 + 1.5 + 3 \end{aligned}$$

$$\begin{aligned} \text{Solvent: } \text{supply solv.} + \text{flushing solv.} &= \text{dirty flush solv.} + \text{emissions} \\ 2.5 + 4 &= 4.5 + 1 + 1 \end{aligned}$$